

Booster Modeling and Space Charge Study

W. Chou for the Booster Study Group
Fermilab
July 22, 2003

Presentation to the DOE Review Proton Source Sub-Committee
July 21-23, 2003, Fermilab

Booster Study Group

- ◆ Beams Division

- Beam Physics Dept: *A. Drozhdin, J. MacLachlan, E. Malamud, L. Michelotti, F. Mills, K.Y. Ng, S. Ohnuma, F. Ostiguy, W. Chou*
- Proton Source Dept: *C. Ankenbrandt, X. Huang, J. Lackey, E. McCrory, D. Moehs, M. Popovic, E. Prebys, R. Tomlin, X. Yang*
- External Beams Dept: *P. Lucas*
- Main Injector Dept: *B. Brown, D. Wildman*
- Mechanical Support Dept: *M. Foley*
- Electrical Support Dept: *D. Wolff, J. Lentz*

- ◆ Technical Division: *J. DiMarco, H. Glass, D. Harding, V. Kashikhin, P. Schlabach*

- ◆ Computing Division: *J. Amundson, P. Spentzouris*

- ◆ Universities: *L. Coney, C. Jacobs, L. Klamp, S. Kopp, D. Michael, H. Zhang, R. Zwaska*

Web site: <http://www-bd.fnal.gov/pdriver/booster/>

Study Goals

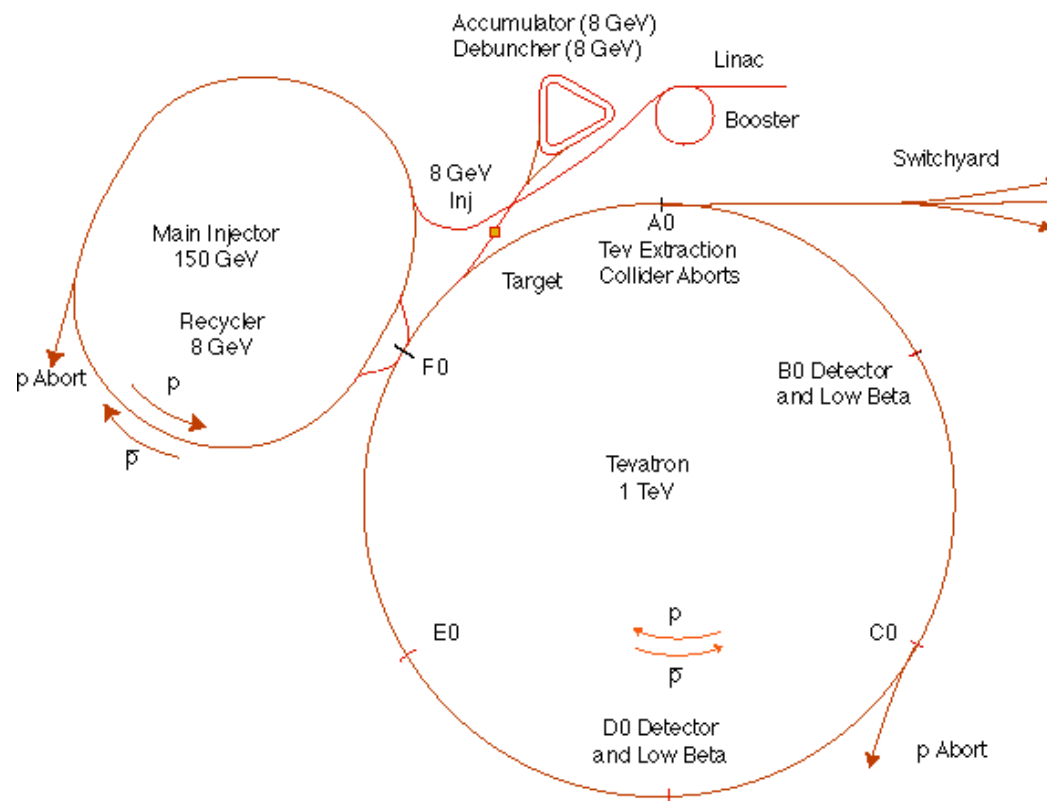
- ◆ To establish a realistic and useful Booster model
 - Inherited a bare FODO lattice model
 - Now it includes the correction package (steering magnets and trim quads), sextupoles, octupoles, gamma-t jump quads, injection orbit bump, doglegs, septa, BEX magnet, etc.
- ◆ To understand the beam loss and emittance blowup mechanism, and the roles of space charge and other associated effects
- ◆ To carry out both simulations and measurements
- ◆ To investigate possible measures for performance improvement

Outline of the Talk

- ◆ Introduction
 - Booster – the bottleneck
 - Parameter list
- ◆ Linear optics modeling - the dogleg effect
- ◆ Space charge study
- ◆ The first 3 milliseconds in the Booster
- ◆ Space charge reduction
- ◆ 2nd order optics modeling - chromaticity
- ◆ Gamma-t jump modeling
- ◆ Power supply experiments at E4R

Fermilab Accelerator Complex

Fermilab Tevatron Accelerator With Main Injector

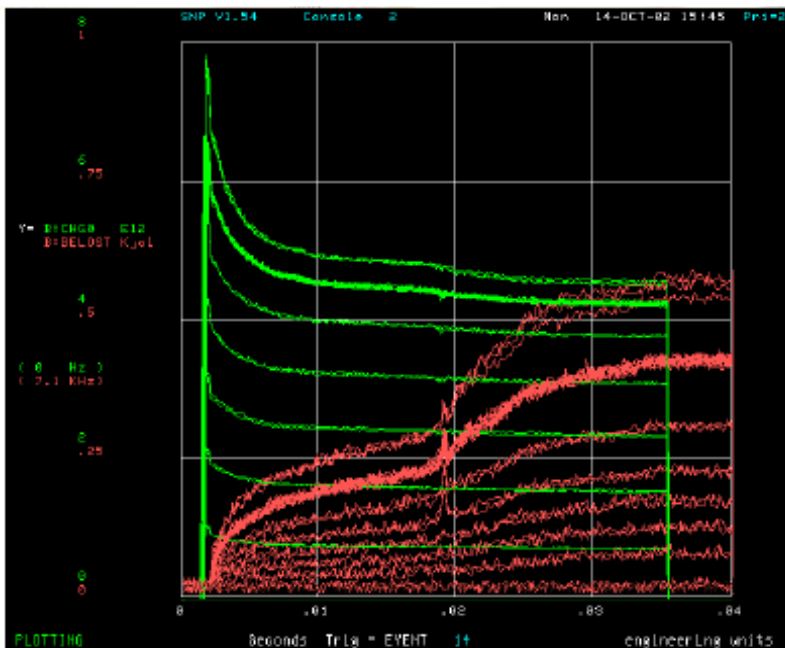


Booster – the Bottleneck

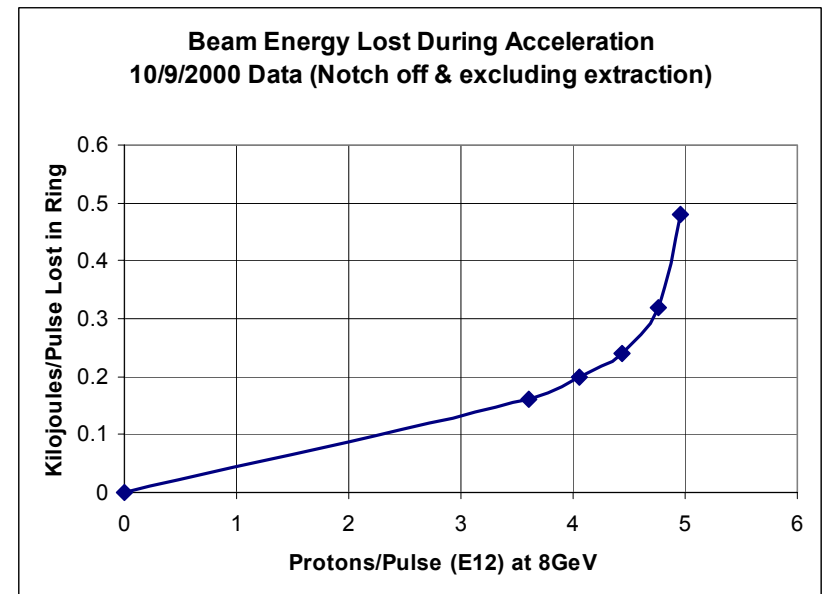
- ◆ The Booster is a 30 years old machine and has never been upgraded.
- ◆ The 400-MeV Linac can provide $25e12$ particles per Booster cycle.
- ◆ The 120-GeV Main Injector can accept $25e12$ protons per Booster cycle.
- ◆ However, the 8-GeV Booster can only deliver $5e12$ particles per cycle.

Booster Beam Loss


(courtesy R. Webber)



For 0, 2, 4, 6, 8, 10, 12, 14 Injected Turns



How Do Particles Get Lost?

- ◆ The Booster up-ramp cycle is 33.3 ms
- ◆ **The first 3 ms** – big loss ($\sim 30\%$):  **This talk**
 - The dogleg effect – reducing machine acceptance
 - Space charge – diluting beam emittance
- ◆ **Transition crossing**: several percent loss
- ◆ **After transition - coupled bunch instability**: a few percent loss

Booster Parameter List

Circumference (m)	474.2
Average machine radius (m)	75.47
Injection kinetic energy (MeV)	400
Extraction kinetic energy (GeV)	8
Repetition rate (Hz)	15
RF frequency (MHz)	37.87 – 52.81
Harmonic number	84
Protons per bunch	6×10^{10}
Protons per cycle	5×10^{12}
Protons per second*	2.5×10^{13}
Protons per hour*	9×10^{16}
Average beam current* (μA)	4
Average beam power* (kW)	32
(*) <i>MiniBooNE continuous operation at 5 Hz</i>	
Lattice	FOFODODO
Super-periodicity	24
Cell length (m)	19.758
Length of combined function magnet (m)	2.889612
Magnet per cell	4
Magnet total	96
Number of straight sections	24 Long, 24 Short, 48 Mini

Booster Parameter List (cont...)

Length of each straight section (m)	6(Long), 1.2(Short), 0.5(Mini)
Max/Min β_x (m)	33.67 (Short)/6.12 (Long)
Max/Min β_y (m)	20.46 (Long)/5.27 (Short)
Max/Min D_x (m)	3.19 (Long)/1.84 (Short)
Phase advance per cell ϕ_x, ϕ_y (degree)	100.5, 102
Horizontal, vertical tune ν_x, ν_y	6.7, 6.8
Natural chromaticity ξ_x, ξ_y	-9.2, -7.0
Transition γ_t	5.45
Transition momentum (GeV/c)	5.03
Transition crossing moment (ms)	17
β at injection, extraction	0.713, 0.994
γ at injection, extraction	1.426, 9.526
η at injection, extraction	-0.458, 0.0227
Revolution frequency at injection, extraction (kHz)	450.8, 628.7
Revolution time at injection, extraction (μ s)	2.22, 1.59
Injection turns (typical)	11
Injection time (typical, μ s)	24.4
Injection linac peak current (typical, mA)	40
Maximum Laslett tune shift	0.4
Normalized transverse emittance ϵ_N (95%, mm-mrad)	12 π
Longitudinal emittance (95%, eV-s)	0.1

The Dogleg Effect

- ♦ A dogleg is a set of 4 orbit bump magnets located in the injection and/or extraction areas.
 - Injection area: to create orbit bump for H⁻ injection. (pulse length ~60 μs)
 - Extraction area: to increase the aperture at the septum. (dc)
- ♦ The *dogleg effect* is referred to the edge focusing of these orbit bump magnets.
- ♦ In the past 30 years, this dogleg effect was ignored in the Fermilab Booster, because it was considered to be “small perturbation.” However, it is not small at all. (first pointed out by A. Drozhdin)
- ♦ The edge focusing strength is:
$$1/f = \tan\theta/\rho \cong \theta^2/L$$

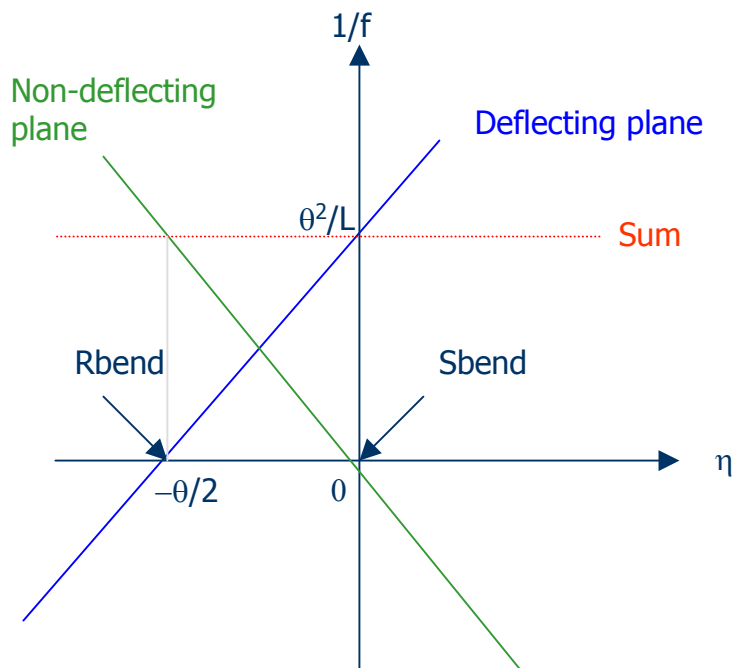
θ - bend angle (60 mrad), ρ - bend radius, L – magnet length (26 cm).
- ♦ The sum of edge focusing of the two extraction doglegs (0.1152 m⁻¹) almost equals to that of one main quadrupole (0.1567 m⁻¹), thus causing large perturbation to the lattice.

The Dogleg Effect (cont...)

- ♦ The doglegs are R-bends (horizontal or vertical) . Their edge focusing gives large perturbation in the non-deflecting plane (vertical or horizontal):
 - $\beta(x)_{\max}$: 33 m \rightarrow 47 m
 - $\beta(y)_{\max}$: 20 m \rightarrow 26 m
 - $D(x)_{\max}$: 3 m \rightarrow 6 m
 - Machine acceptance: $16\pi \rightarrow 8\pi$, reduced by 50% !
- ♦ Beam measurement agreed with the model.
- ♦ Removal of one of the two doglegs led to immediate improvement:
 - Beam loss cut to half
 - A milestone of the MiniBooNE experiment reached (5e16 protons per hour)
 - \rightarrow champagne celebration

Edge Focusing of a Wedge Magnet

Focusing strength as a function of edge angle η



L = magnet length

θ = bend angle

η = edge angle

Sector magnet (Sbend): $\eta = 0$

Rectangular magnet (Rbend): $\eta = -\theta/2$

Focusing strength: (> 0 focusing)

Deflecting plane:

$$1/f = 2\eta\theta/L + \theta^2/L$$

Non-deflecting plane:

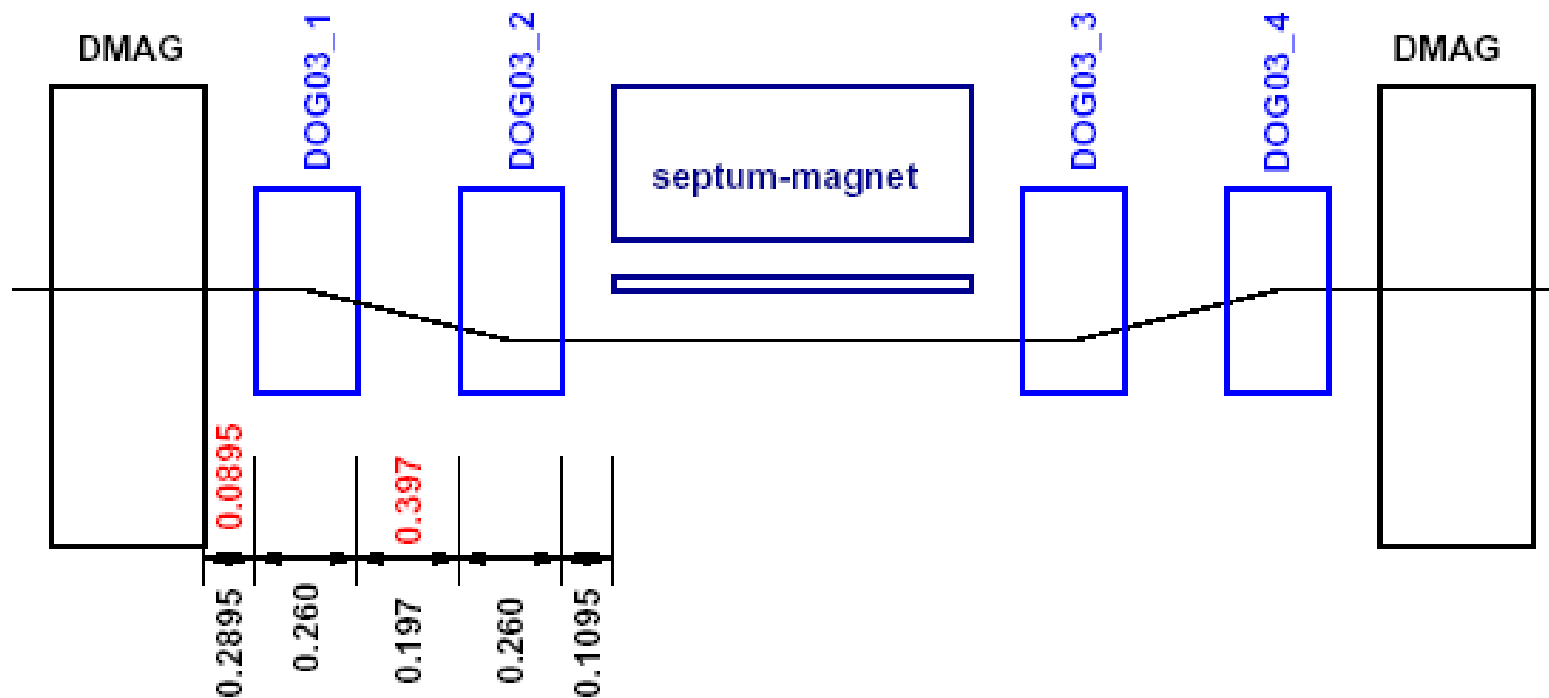
$$1/f = -2\eta\theta/L$$

Sum = θ^2/L (always focusing!)

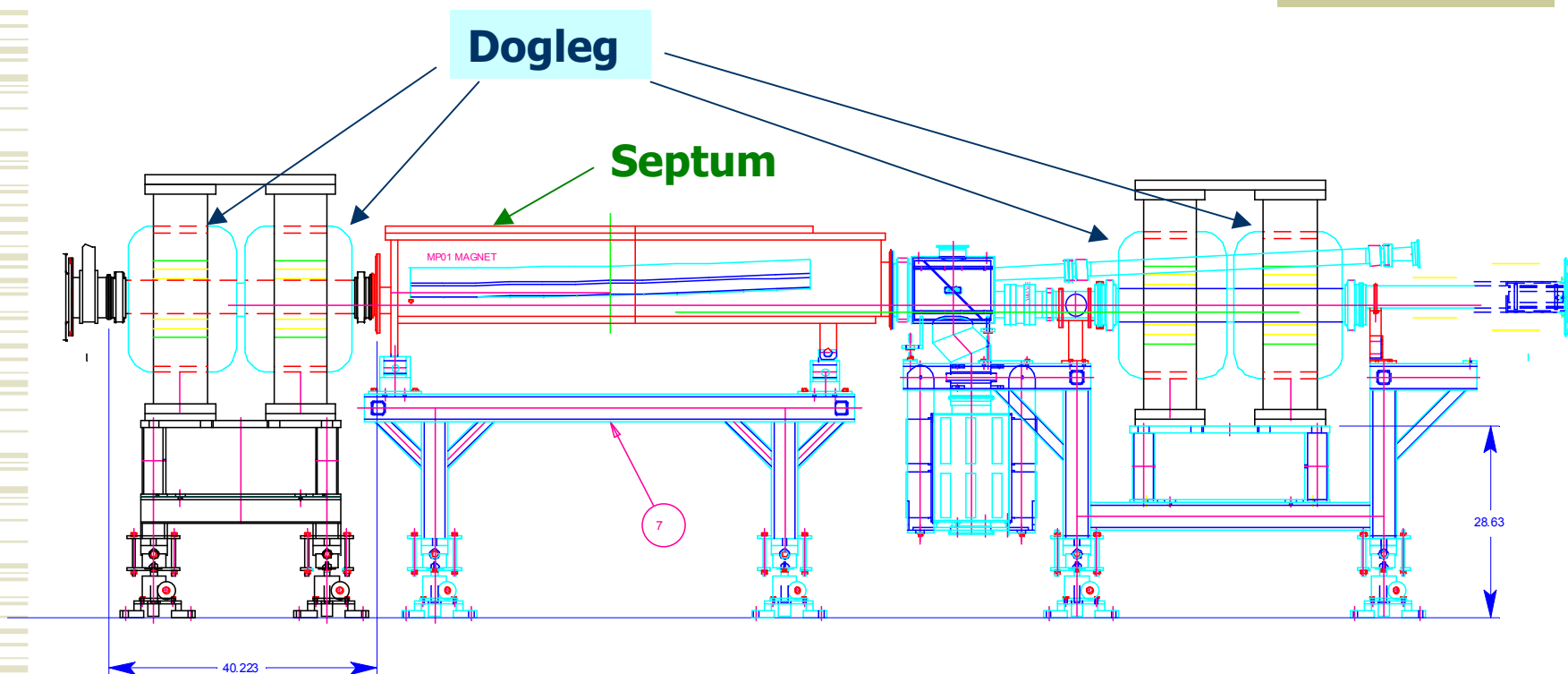
To be more precise, this sum is from the body focusing in the deflecting plane. The sum of the edges in the two planes is zero.

Dogleg Layout Sketch

(courtesy A. Drozhdin)

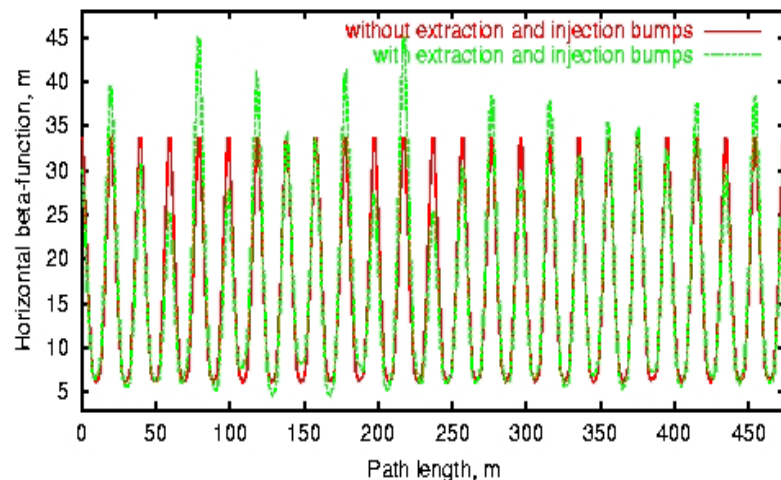


Present Dogleg Layout (courtesy J. Lackey)

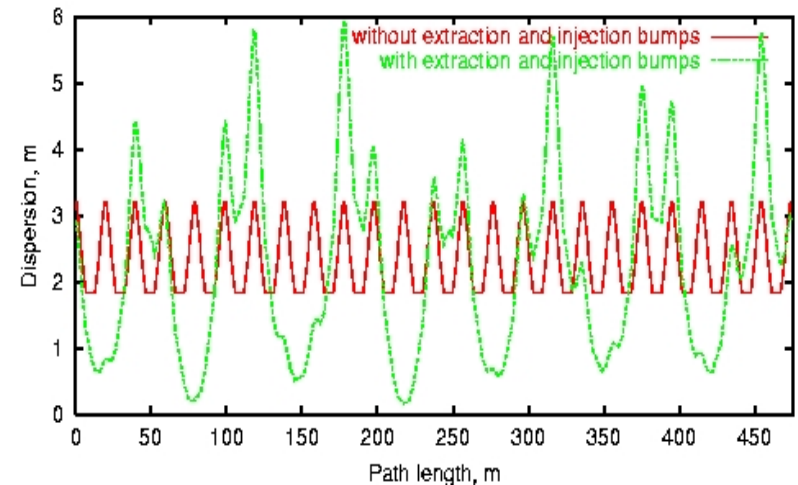


Dogleg Perturbation on Linear Lattice: MAD Simulation

(courtesy A. Drozhdin)



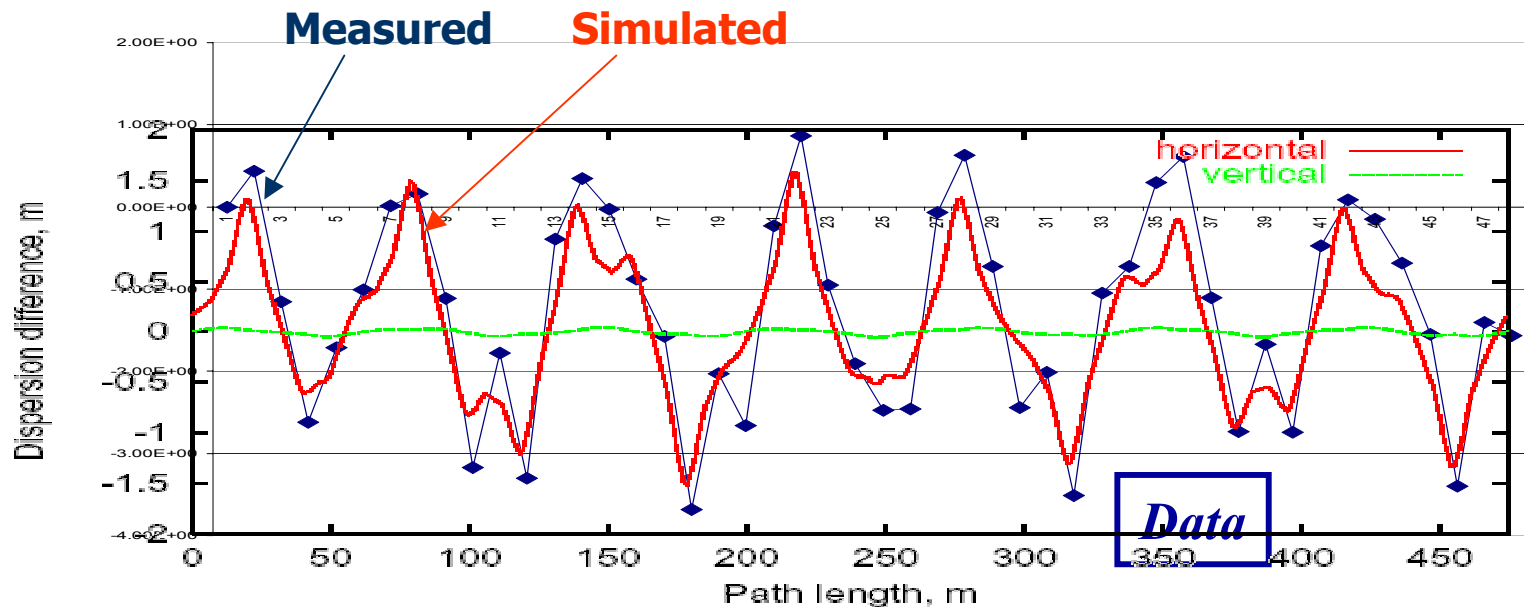
Horizontal beta-function



Horizontal dispersion

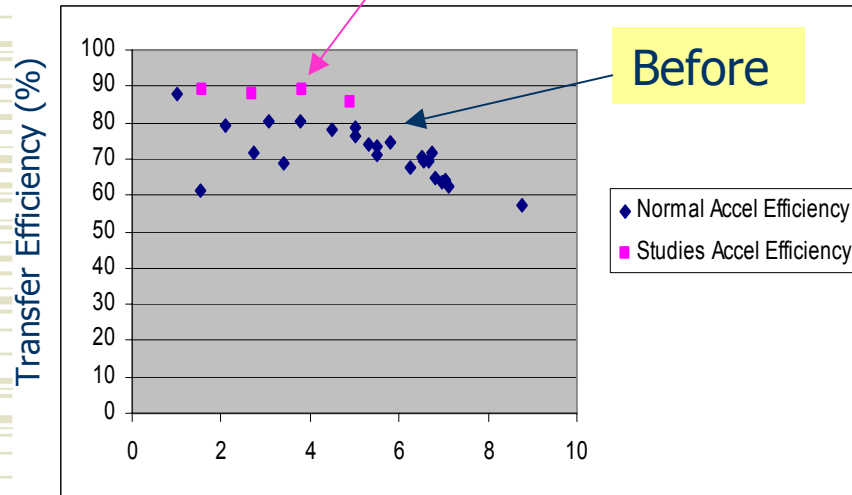
Dogleg Perturbation on Dispersion: Simulation *vs.* Measurement

(courtesy E. McCrory)



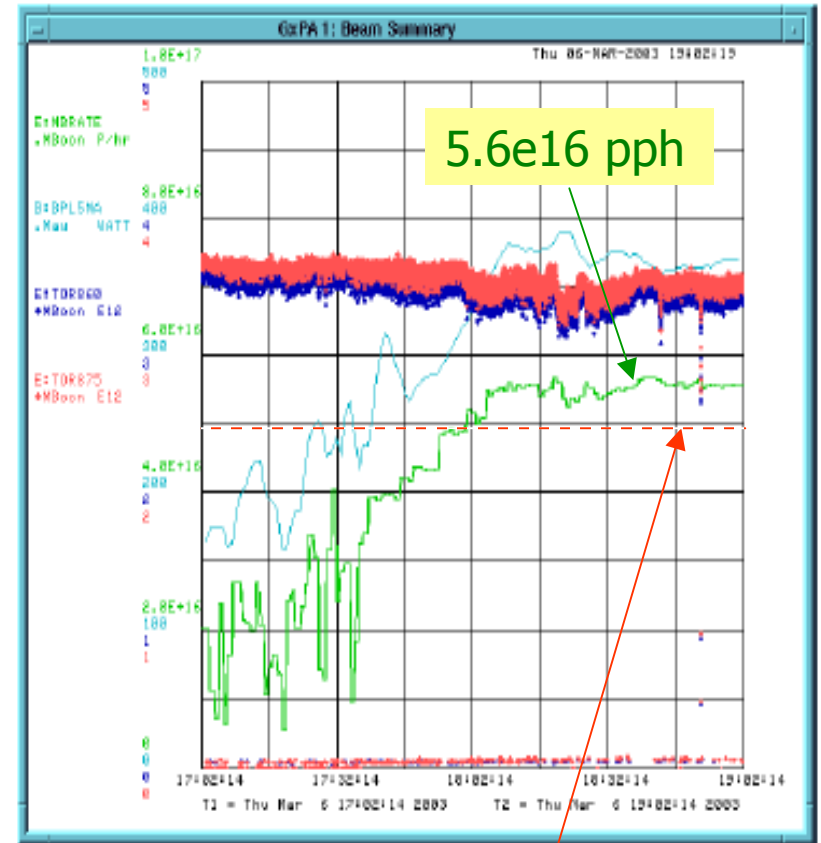
Beam Experiment: Removing One of the Two Doglegs

After, beam loss cut by half



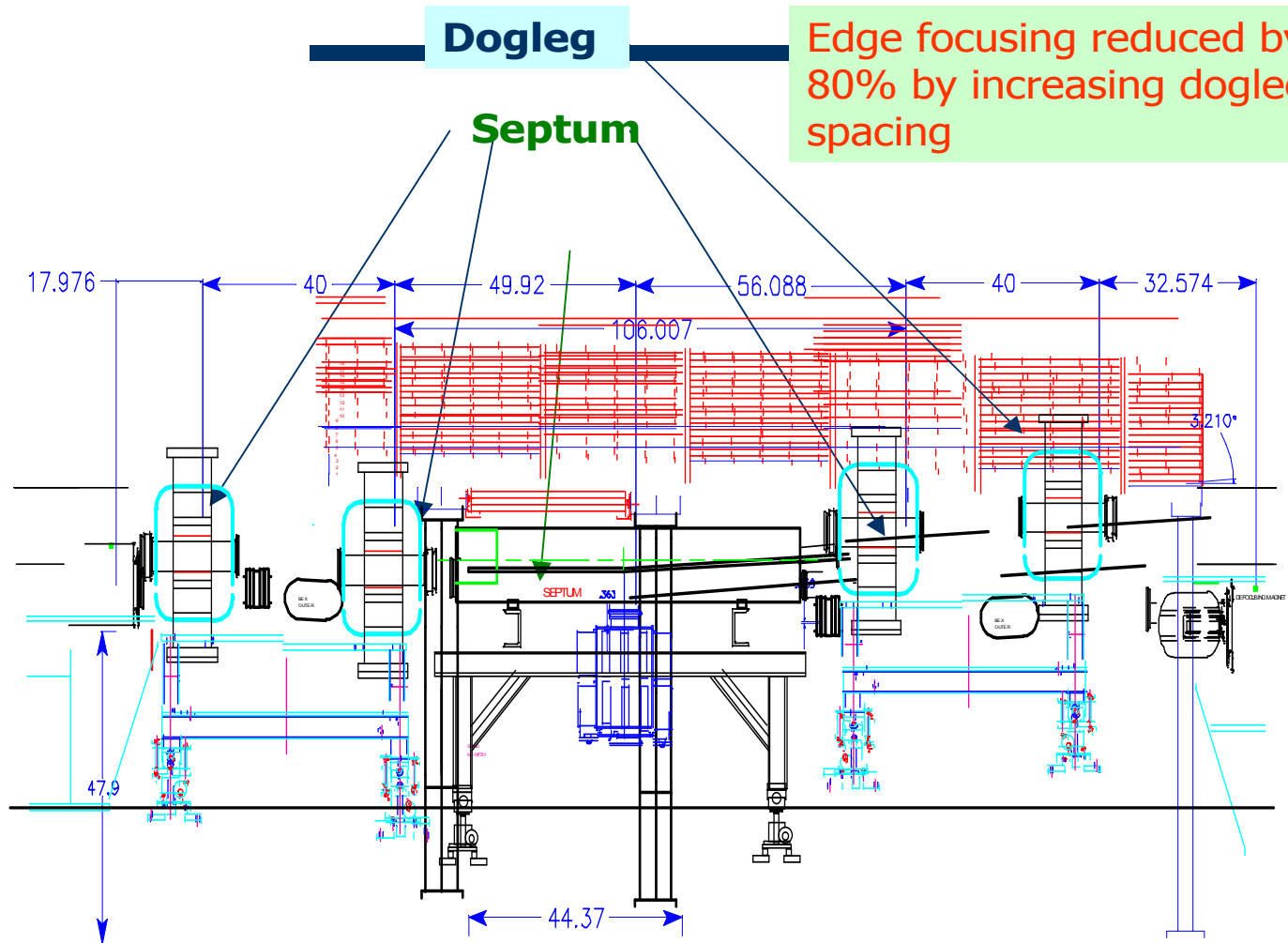
Injected beam intensity ($\times 10^{12}$)

(Courtesy J. Lackey)



MiniBooNE milestone: 5e16 pph

New Dogleg Layout (courtesy J. Lackey)



Application to Other Machines - KEK Booster

- ◆ KEK Booster has four horizontal bump magnets for H⁻ injection:

θ (mrad)	140	-180	-100	140
-----------------	-----	------	------	-----

L (m)	0.349	0.449	0.249	0.349
---------	-------	-------	-------	-------

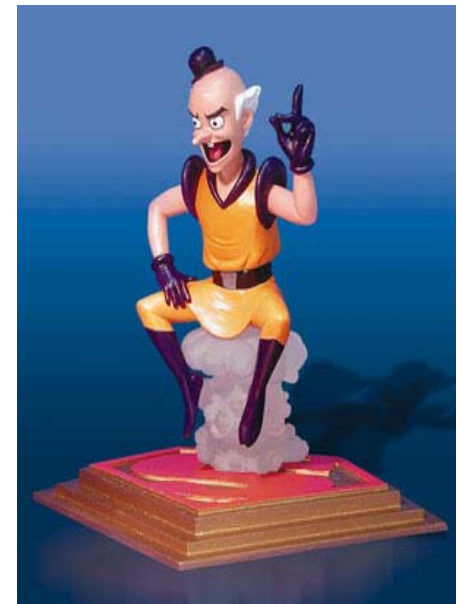
total edge focusing strength: $\sum \theta^2/L = 0.2246 \text{ m}^{-1}$

- ◆ KEK Booster main quadrupole strength: $1/f = 0.6987 \text{ m}^{-1}$
- ◆ So the additional focusing is about 1/3 of a main quadrupole and is in the vertical plane.
- ◆ SYNCH shows about 30% increase in $\beta(y)_{\text{max}}$ with the dogleg effect.
- ◆ *How about AGS Booster or CERN PS Booster?*

Space Charge Study

Simulation code development:

- **1-D ESME** (P. Lucas, J. MacLachlan)
- **2-1/2-D ORBIT** (F. Ostiguy, L. Michelotti, W. Chou)
 - Original parallelized code obtained from SNS (J. Holmes, J. Galambos)
 - Add in map generation using Mxyzptlk/beamline C++ class libraries
 - MAD parser (FNAL Lex/Yacc based parser)
 - Replace (the now obsolete) Supercode shell with Python
 - Improvements in code efficiency; support for acceleration (work in progress)
 - Numerous bug fixes

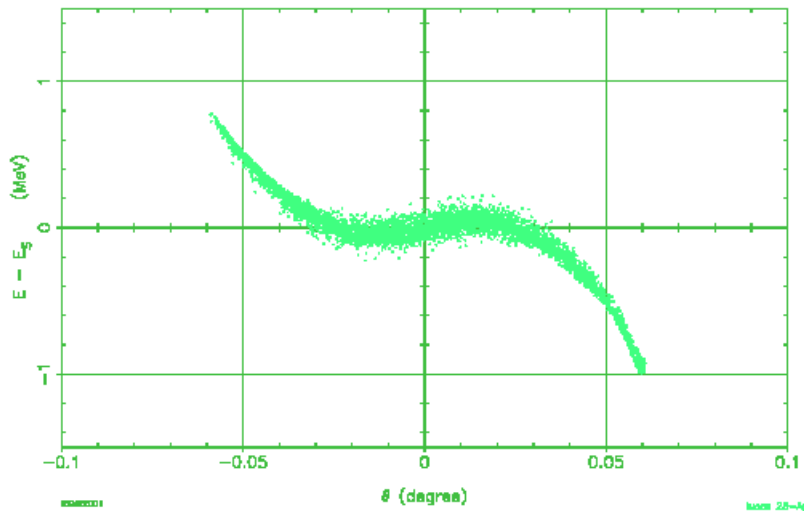


Michelotti's Mxyzptlk

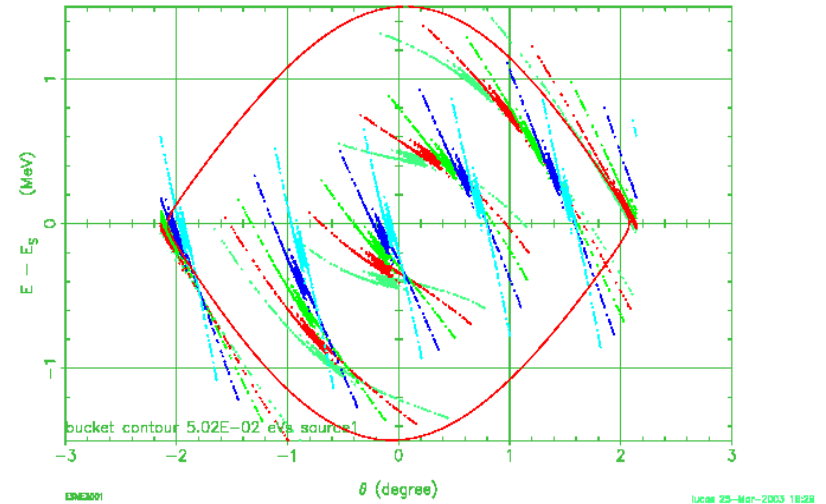
Space Charge Study (cont...)

- **3-D Synergia** (P. Spentzouris, J. Amundson, in collaboration with L. Michelotti, F. Ostiguy)
 - Modification of the linac space charge code IMPACT for circular machines
 - Split operator technique
 - Parallel PIC code
 - Use the same MAD parser
 - Use the same Mxyzptlk/beamline C++ class libraries to compute map coefficients; propagation handled by IMPACT
 - Linear map (could use higher order)
 - Up to 5M particles on 65x65x65 grid
 - Funded by the DOE SciDAC project
 - References: Fermilab-Conf-03-126-E, Fermilab-Conf-03-127
 - Web: http://cepa.fnal.gov/psm/aas/Advanced_Accelerator_Simulation.html

Linac 805 MHz Microbunches (ESME, courtesy P. Lucas)

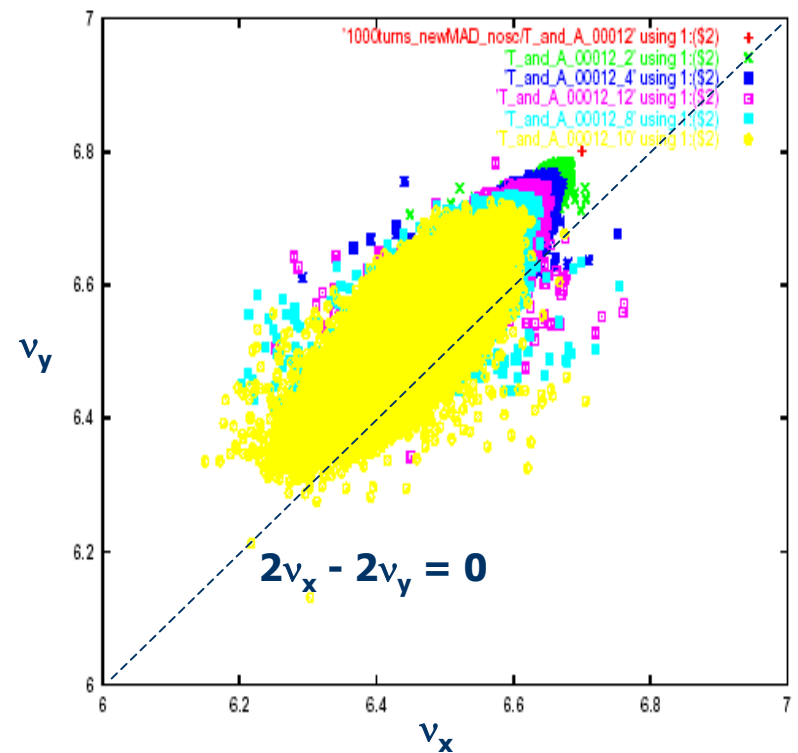
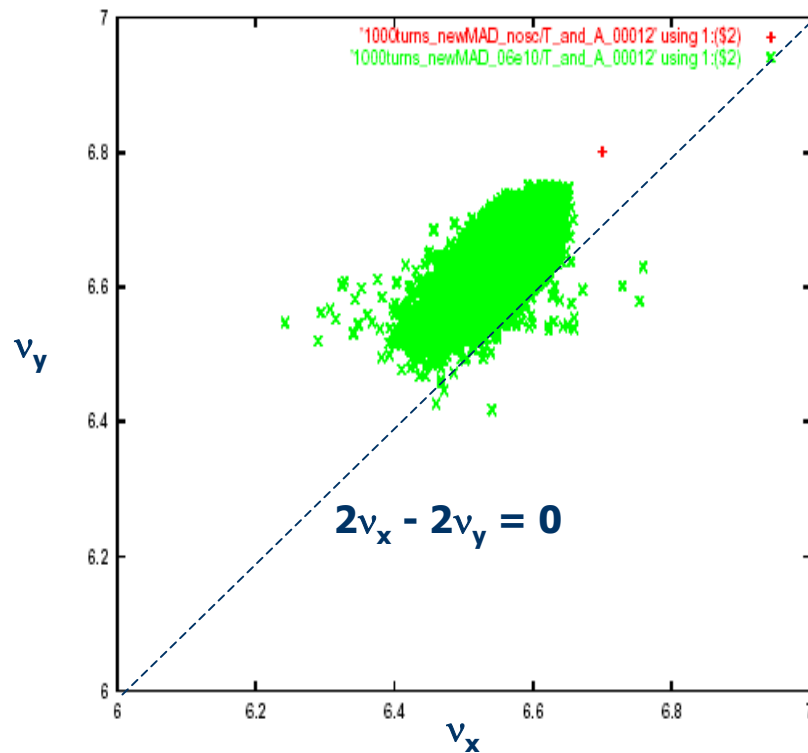


One microbunch with $\Delta p/p = \pm 0.13\%$



Multi-turn injection

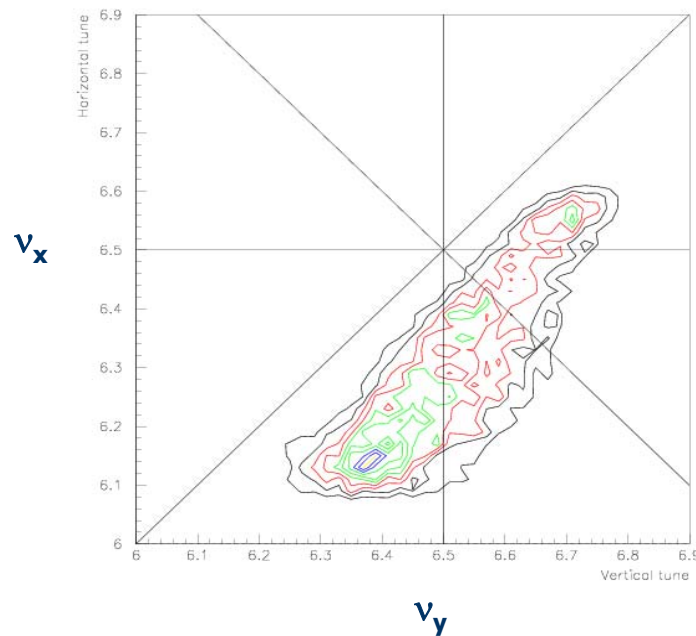
Tune Footprint (ORBIT, varying beam intensity)



Laslett tuneshift: $\Delta v \approx -0.3$

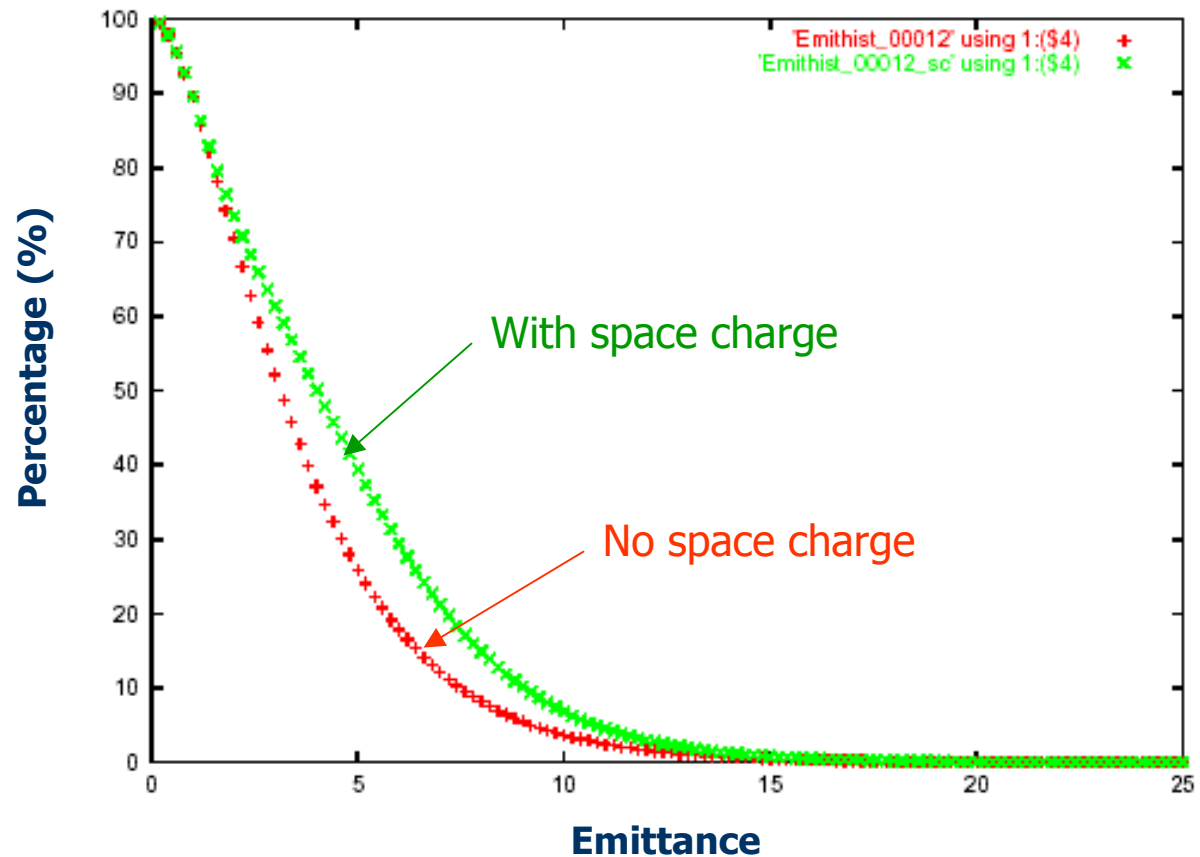
Tune Footprint

(Synergia, courtesy P. Spentzouris)



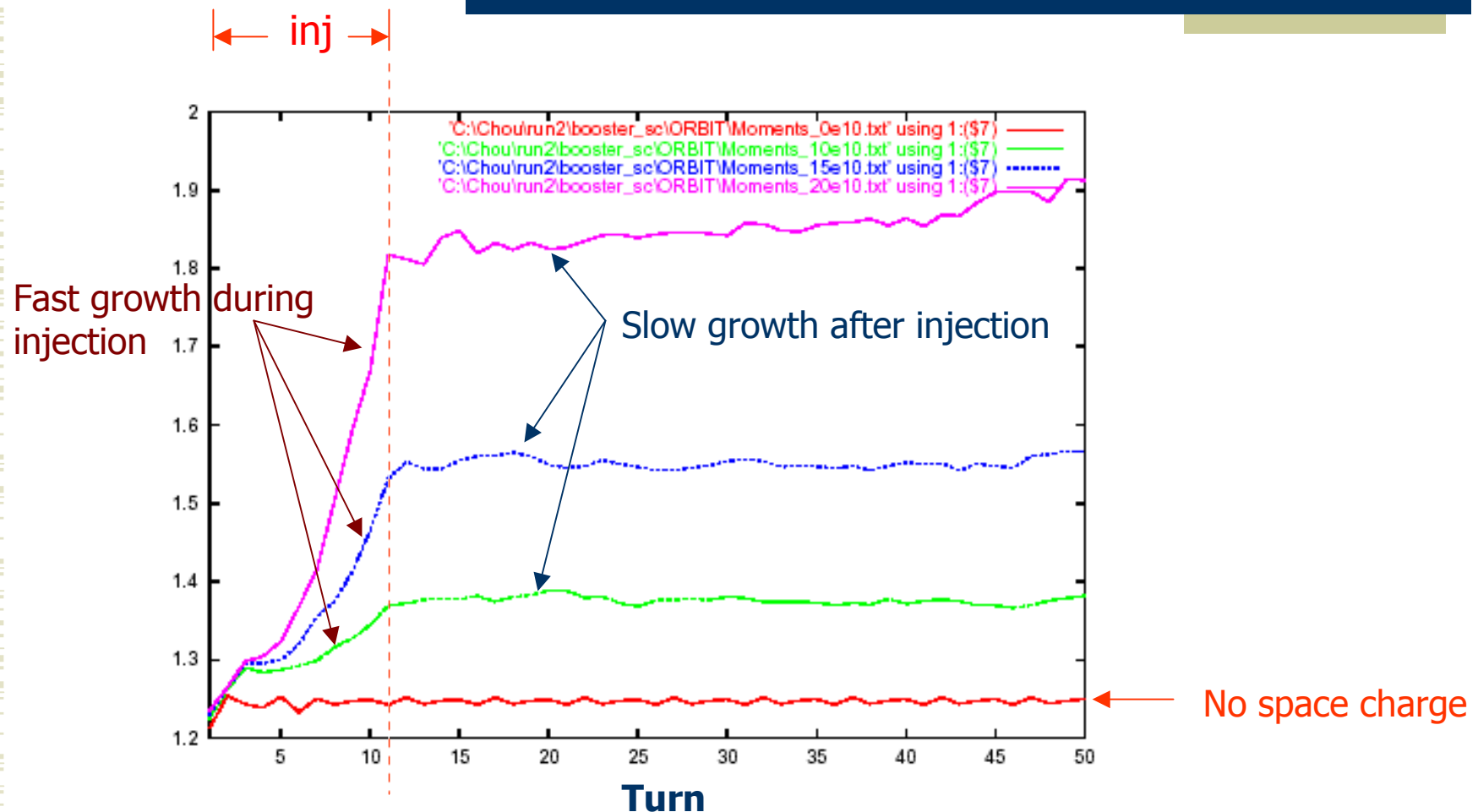
outer contour 90%
particles

Emittance Histogram (ORBIT)



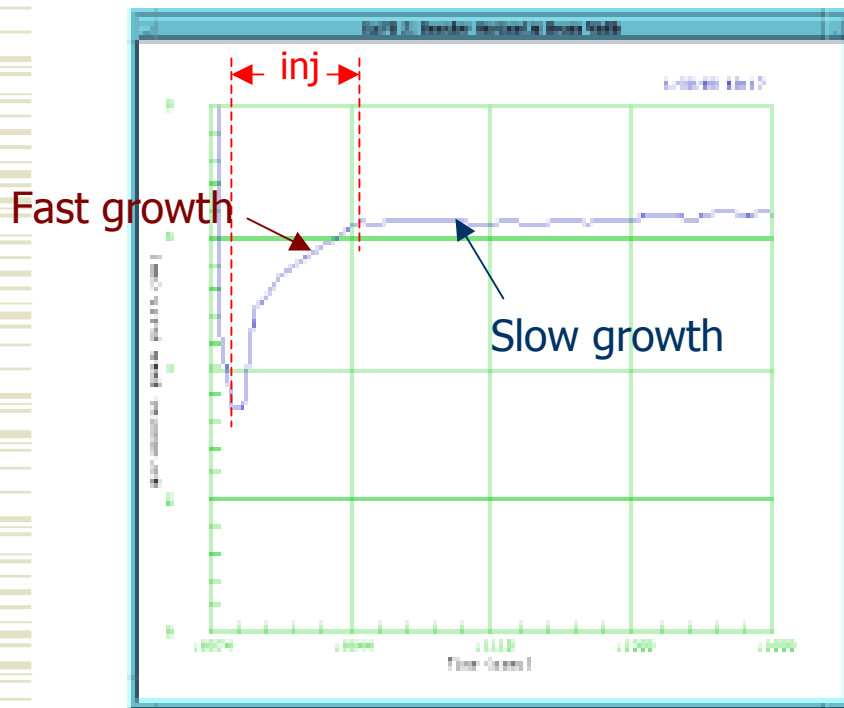
Emittance Growth

(ORBIT, 11-turn injection, varying beam intensity)



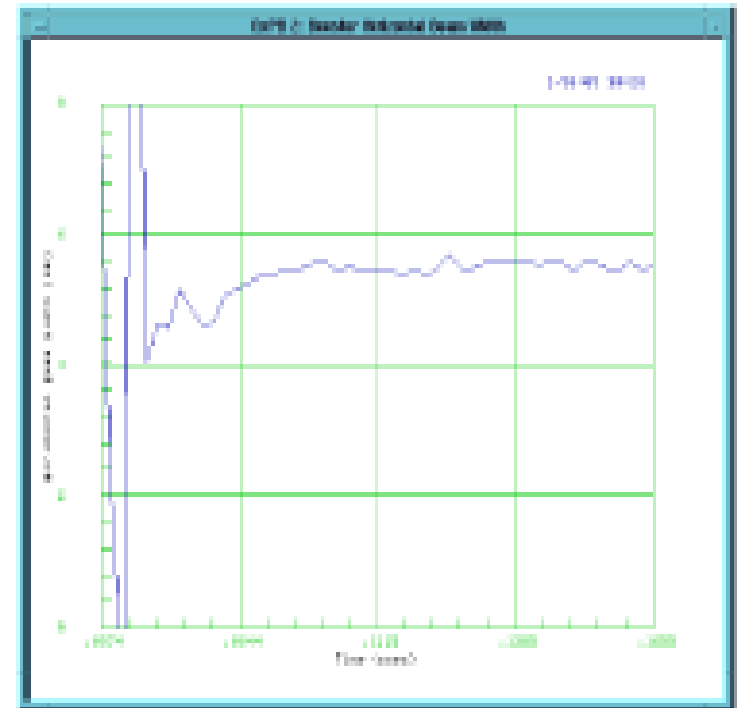
IPM Measurement (Raw data)

40 mA, 10-turn injection



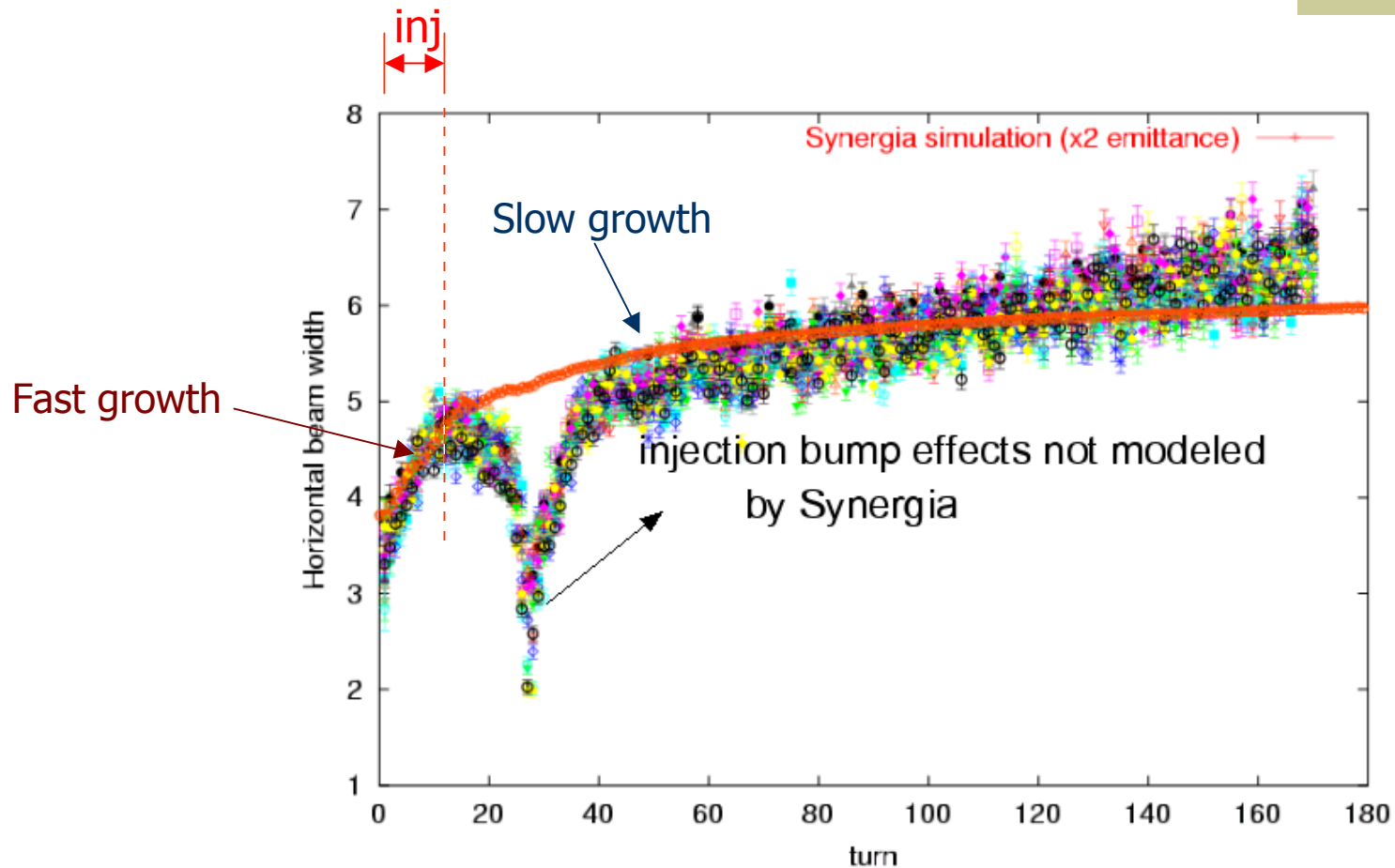
45 turns

20 mA, 10-turn injection

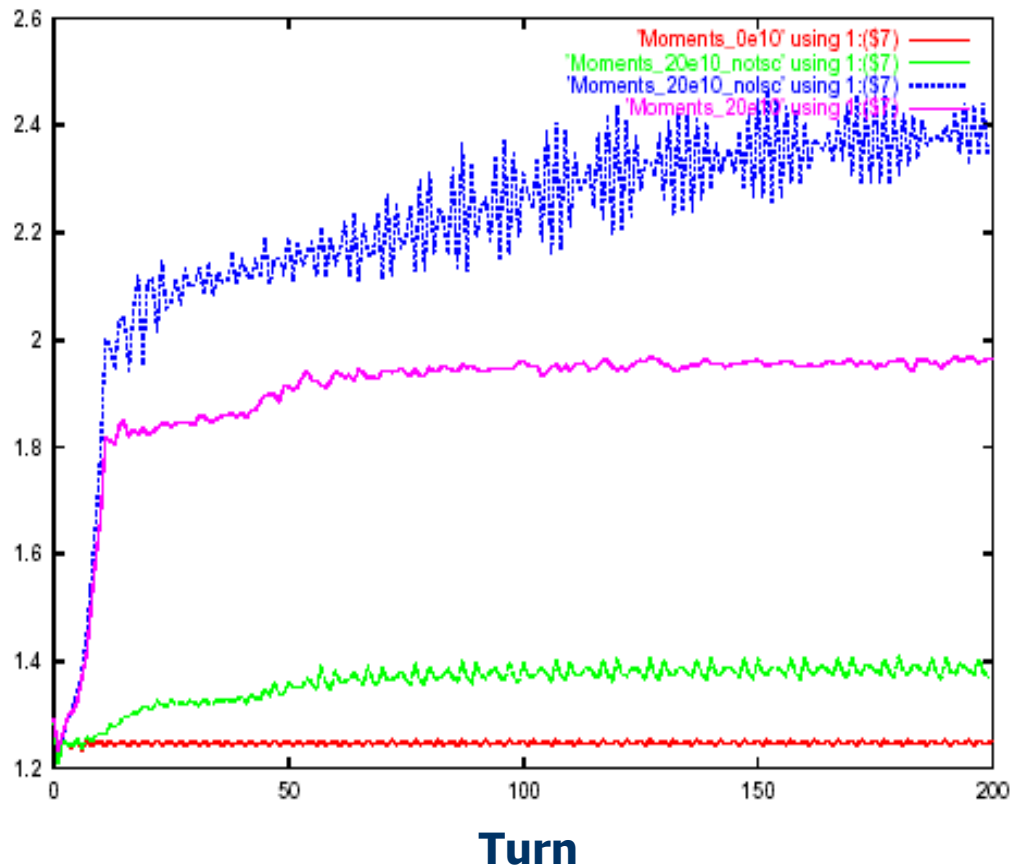


Emittance Growth

(Synergia, processed IPM data, courtesy P. Spentzouris)



Emittance Growth (cont...)



← Transverse sc only

← Transverse + Longitudinal

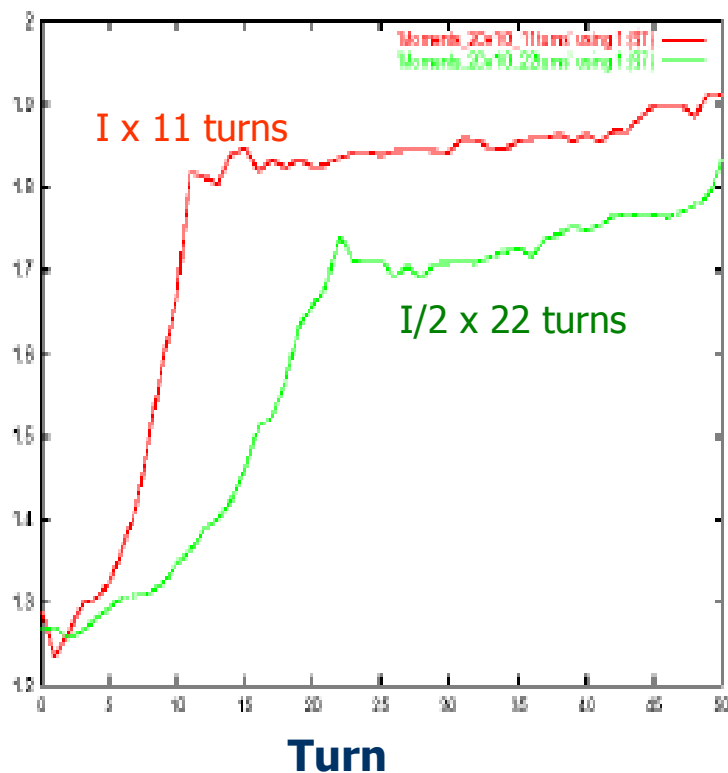
← Longitudinal sc only

← No space charge

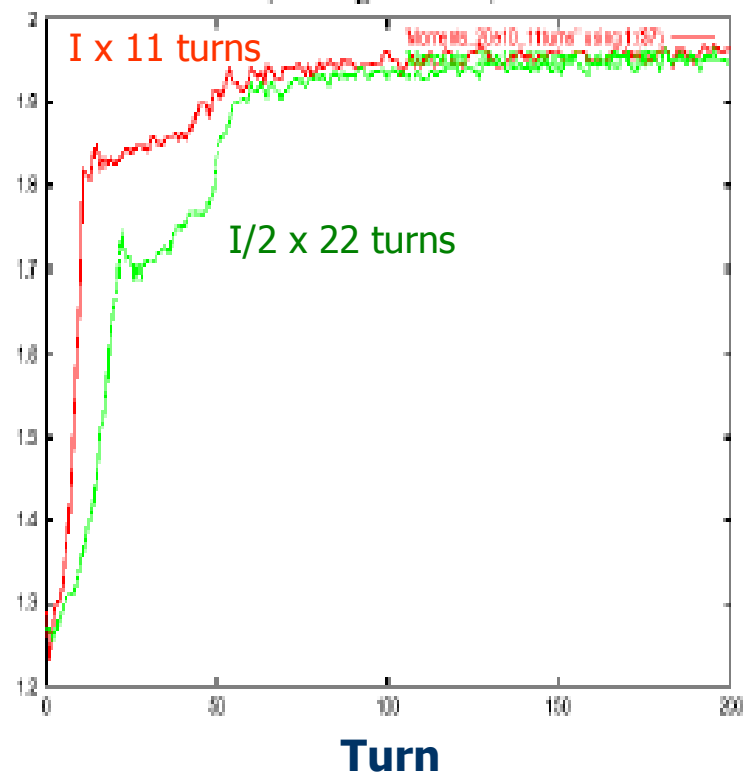
Emittance Growth (cont...)

(varying linac current I and injection turns together)

First 50 turns



First 200 turns



First 3 milliseconds in the Booster

◆ Transverse loss

- The transverse acceptance is:

$$A = \{\beta_{\max} \times \varepsilon_N / \beta\gamma\}^{-1/2} + D_{\max} \times \Delta p/p + \text{c.o.d.}$$

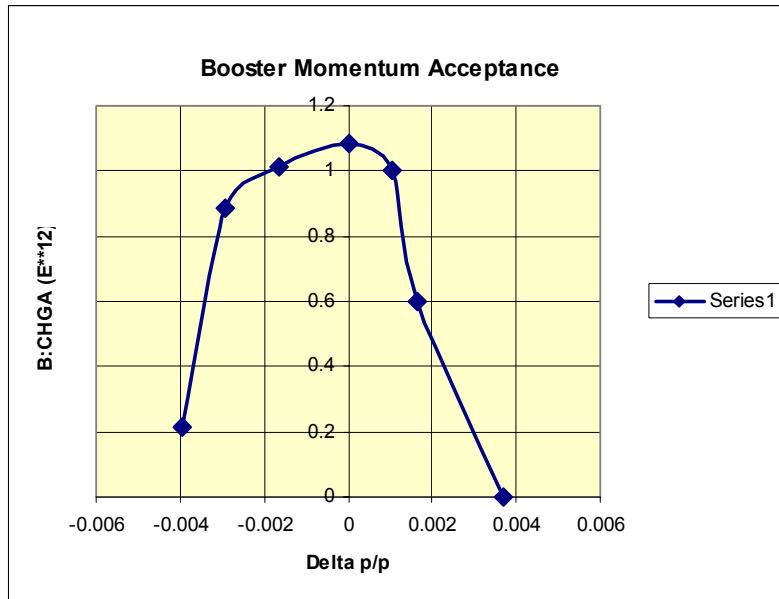
- The magnet good field region is about ± 1.2 inch
- For regular β_{\max} and D_{\max} , the maximum allowable ε_N is about 16π
- But the doglegs blow up the lattice function and reduce ε_N to about 8π
- The incoming linac beam is 7π
- Space charge dilutes the emittance during the multiturn injection, resulting in loss.

◆ Longitudinal loss

- The measured Booster momentum acceptance is small: $\pm 0.15\text{-}0.2\%$
- The measured linac beam momentum spread is about $\pm 0.13\%$
- When the beam is bunched, the momentum spread increases to $\pm 0.3\%$
- This exceeds the acceptance and results in loss

Longitudinal Measurement

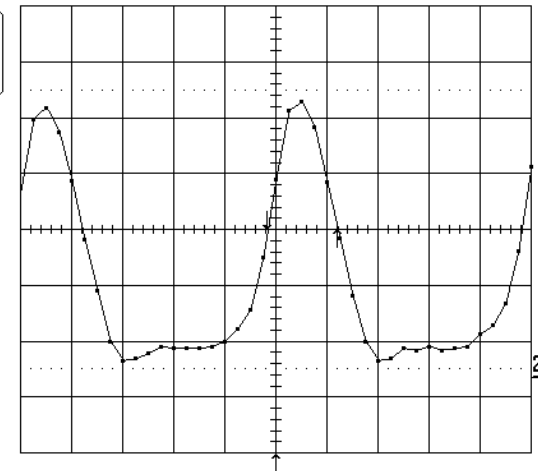
Momentum acceptance



Microbunch length First turn at L18

3-Apr-01
15:42:05

1 ns
20.0mV
0.3mV



1 ns

1 disabled
2 10 mV 500 Ω
3 disabled
4 disabled



Δt 1.365 ns $\frac{1}{\Delta t}$ 732.6 MHz
Ext DC 245mV 50 Ω

4 GS/s

STOPPED

First 3 milliseconds in the Booster (cont...)

When beam energy goes up, the situation improves rapidly:

- ◆ **Transverse:**

- Dogleg focusing strength: $1/f = \theta^2/L \propto 1/p^2 \downarrow\downarrow$
- Beam size due to adiabatic damping: $\varepsilon = \varepsilon_N/\beta\gamma \downarrow$
- Space charge effect $\propto 1/\beta\gamma^2 \downarrow\downarrow$

- **Longitudinal:**

- $\Delta E/E \downarrow$
- $1/\beta^2 \downarrow$
- $\Delta p/p = (1/\beta^2) \times \Delta E/E \downarrow\downarrow$

In the middle and late stage of the cycle, other schemes will contribute to the beam loss (e.g., transition crossing, coupled bunch instability), but which is beyond this topic.

Space Charge Reduction

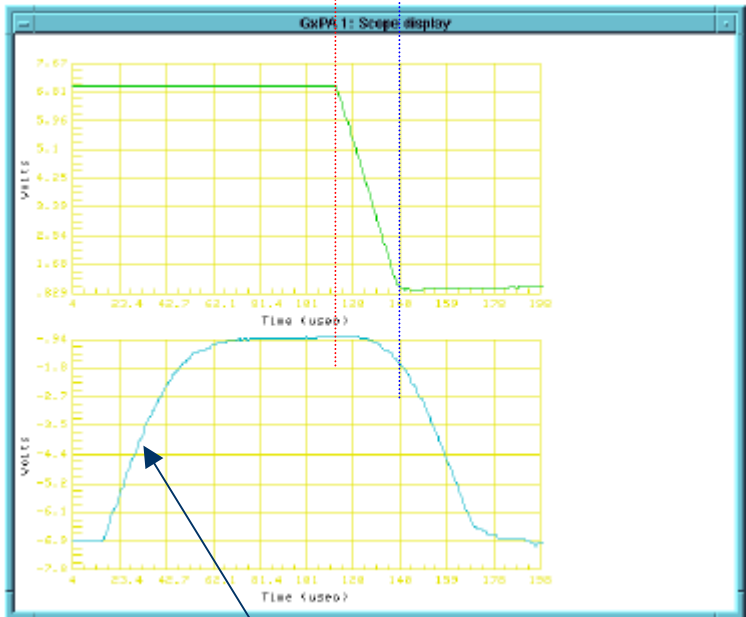
- ◆ Painting experiment
- ◆ Inductive insert experiment
- ◆ Quadrupole pickup
- ◆ IPM improvement
- ◆ (H^- source and linac improvements)
- ◆ (2^{nd} harmonic RF)

Painting Experiment

Adjust injection timing

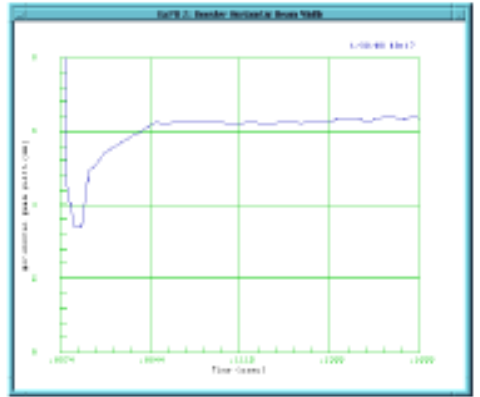
start

end

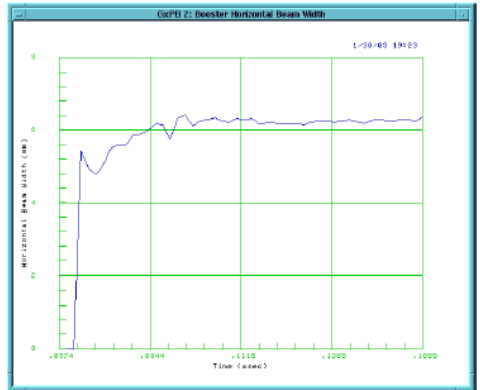


Injection orbit bump

no painting



painting



Inductive Inserts Experiment

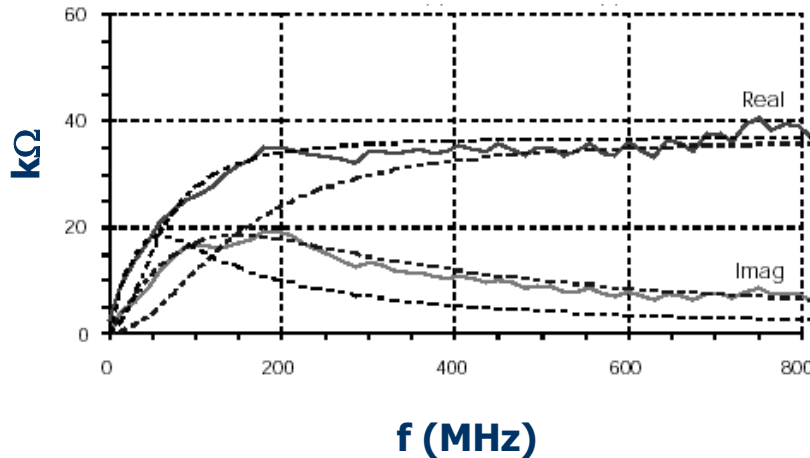


- ◆ Two Fermilab-made modules have been installed in the PSR at LANL. They help increase the PSR beam intensity significantly.
- ◆ Two same modules were installed in the Booster. But no effect on the beam (neither bad nor good).
- ◆ A possible explanation is the inductance not big enough.
- ◆ Five more modules were made and will be tested.

Inductive Inserts Experiment (cont...)

- J. Crisp's measured lamination impedance (96 magnets):

$$Z(\text{lam}) = 37 \text{ k}\Omega + j\omega \text{ } 40 \text{ }\mu\text{H}$$



- Space charge impedance (for $g = 2$):

$$Z(\text{sc}) = -j\omega \text{ } 92 \text{ }\mu\text{H}$$

- D. Wildman's measured inductive insert impedance:

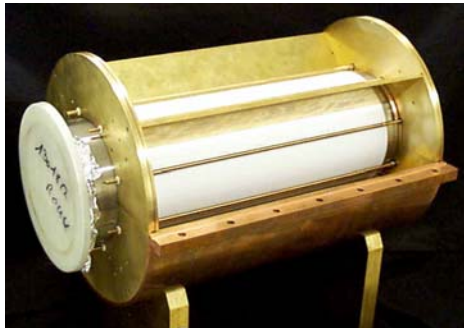
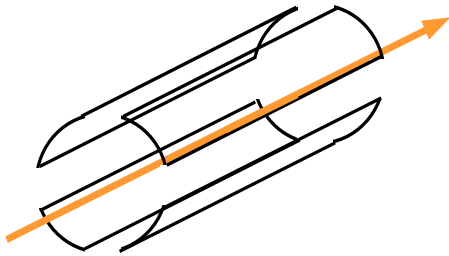
$$Z(\text{ind. insert}) = j\omega \text{ } 4 \text{ }\mu\text{H}$$

per module (30-in long)

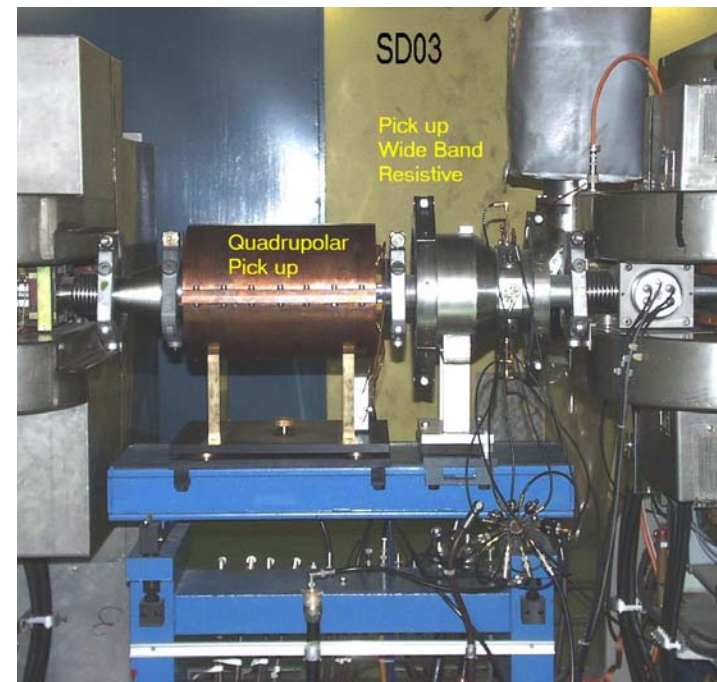
Quadrupole Pickup

(Courtesy A. Jansson)

Magnetic quad pickup



A pickup installed on the CERN PS



IPM Improvement

- ◆ Present two Booster IPMs (one H, one V) collect ions with 10 kV clearing field
- ◆ Consider to increase to 30 kV by using the old MI IPM power supply
- ◆ Investigate the possibility to convert them to electron collection with an external permanent magnetic field (similar to the new ones in MI, RHIC and SPS)



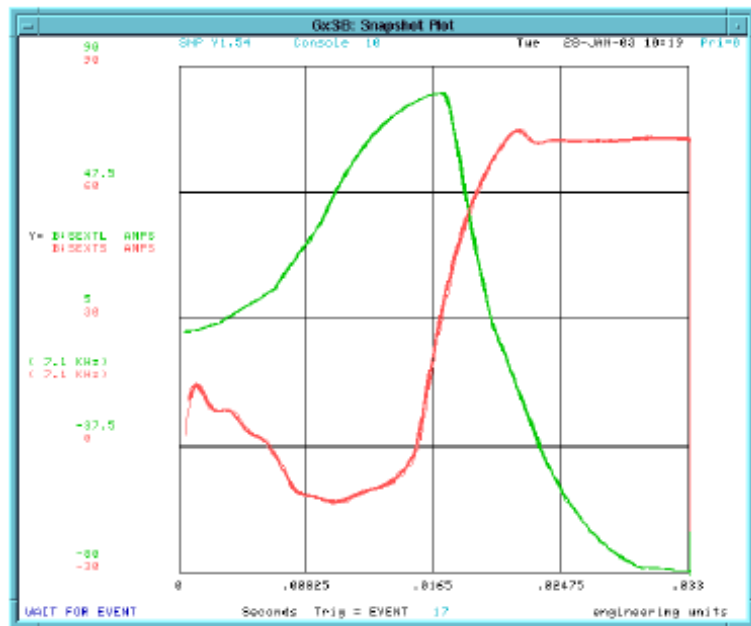
MI IPM (courtesy J. Zagel)



RHIC IPM (courtesy R. Connolly)

Chromaticity Modeling

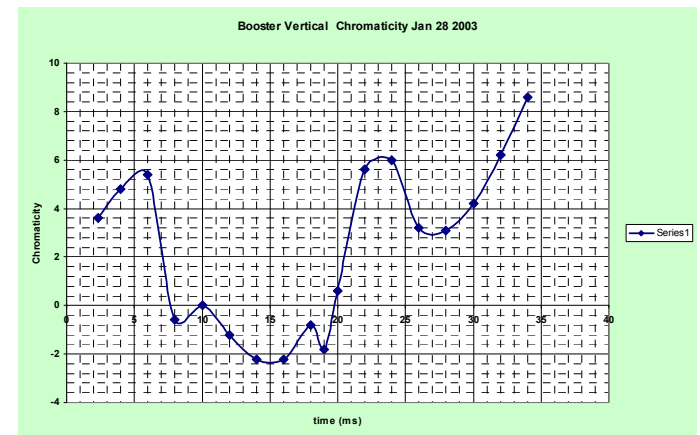
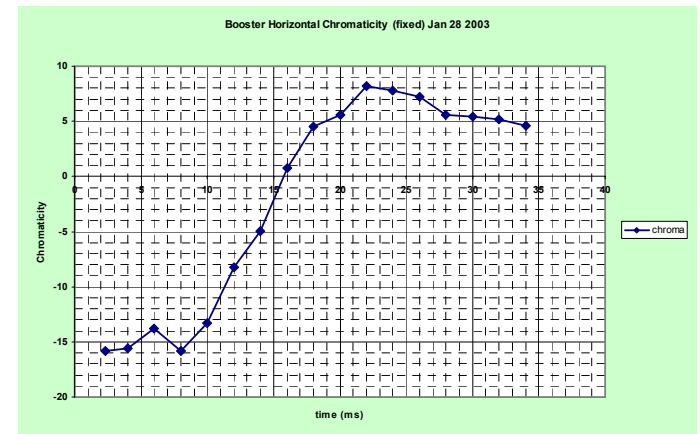
Chromaticity sextupole setting



$\xi(x)$

$\xi(y)$

[zero current @inj: $\xi(x) = -23$, $\xi(y) = +11$]



Chromaticity Modeling (cont...)

$$\xi = \xi(\text{lat}) + \xi(\text{chrom sext}) + \xi(\text{mag sext}) + \xi(\text{dogleg})$$

- ◆ Goal:

To have a **spreadsheet** relating the sextupole current to the machine chromaticity throughout the cycle

- ◆ The task is complicated by two factors:

- The dogleg effect, which perturbs the local lattice function and has an energy dependence (**calculable**)
- The main magnets have large sextupole component, which comes from both the body part and the end packs (**need measurement**)

Chromaticity Calculation

	$\xi(x)$	$\xi(y)$
♦ Bare lattice (Lat)	-9.16679	-7.03638
♦ Lat + dogleg	-9.57427	-7.01265
♦ Lat + body sext	-23.55770	11.65977
♦ Lat + body sext + dogleg	-23.40371	11.00271
♦ Lat + body sext + chrom sext + dogleg	0.04399	-0.18496
♦ Lat + body sext + chrom sext (no dogleg)	3.67119	-11.11968

The doglegs' direct contribution to the chromaticity is small. But their impact on the chromaticity is significant because of the big change of local β and D at the chromaticity sextupoles.

Field Measurement at E4R



A mole used for dc field measurement

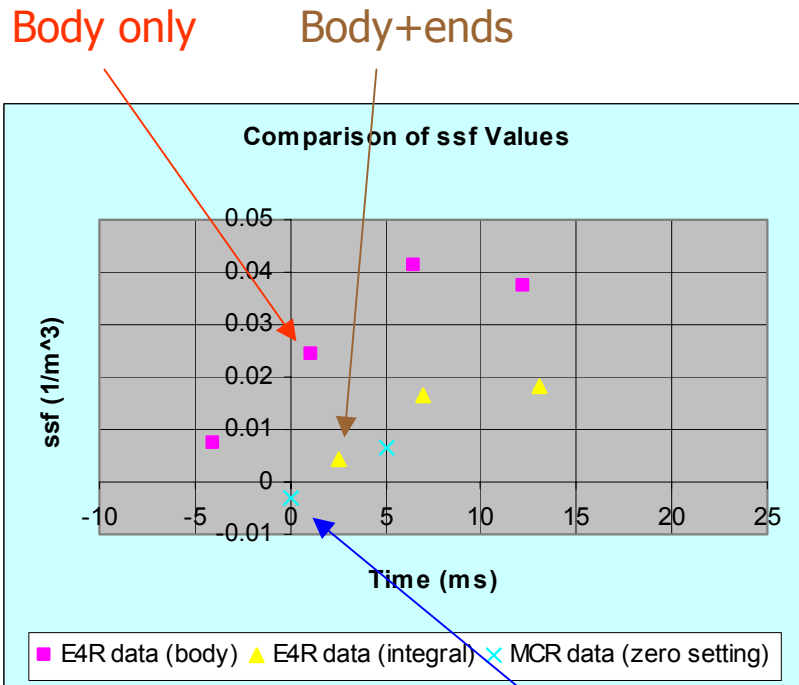
Main Magnet Sextupole Component

- ◆ Two independent measurements:
 - Field measurement at the E4R
 - Chromaticity measurement at the Main Control Room
- ◆ The two teams did not talk to each other on purpose (a blind check)
- ◆ The results are found to be in good agreement at 400 MeV
- ◆ Work in progress for ac measurement

Magnet type	Body only	Body + Ends field measurement	Body + Ends chromaticity measurement
F	0.0242	0.004	-0.003
D	-0.0306	-0.0413	-0.0454

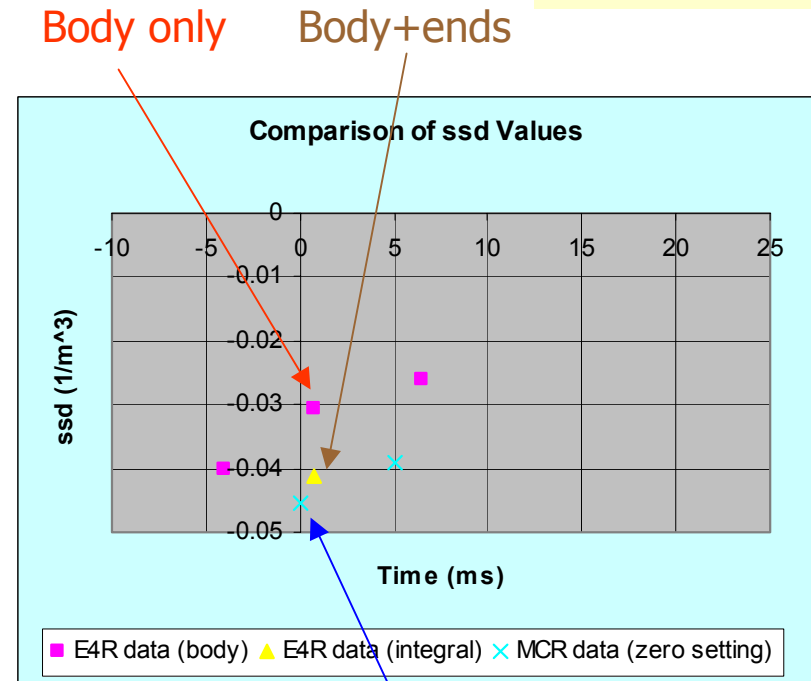
Main Magnet Sextupole Measurements (cont...)

F magnet



Chrom meas.

D magnet

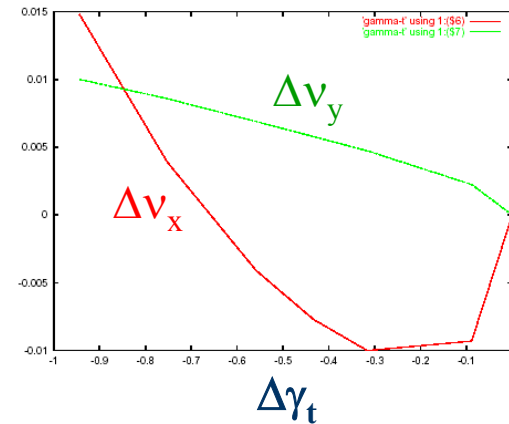
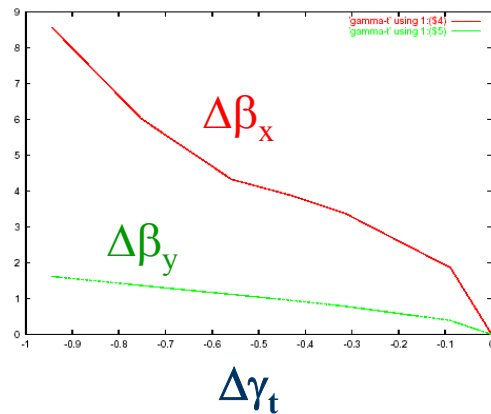
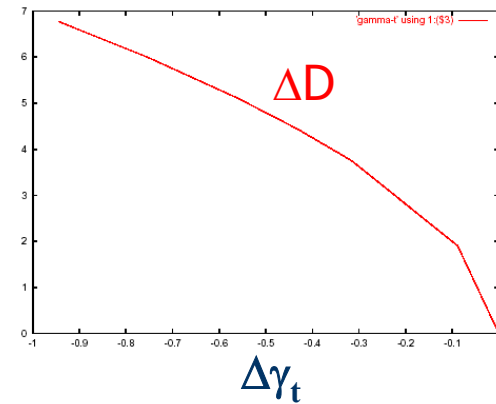
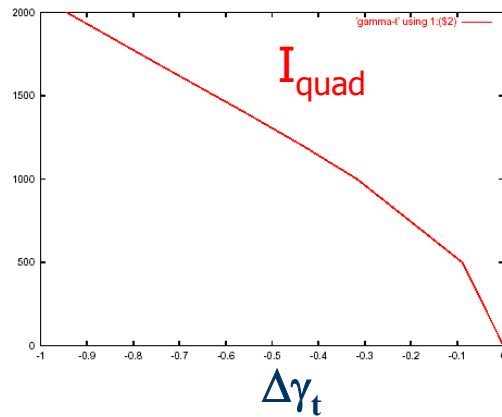


Chrom meas.

Gamma-t Jump Modeling

- ◆ Gamma-t quad location:
 - 6 QF: Short 4, 8, 12, 16, 20 and 24
 - 6 QD: Short 2, 6, 10, 14, 18 and 22
- ◆ Length:
 - QF = 21.6 cm
 - QD = 24.6 cm
- ◆ Stength:
 - $B' = 480 \text{ Gauss/in @ } 2000\text{A}$

Gamma-t Jump Modeling (cont...)

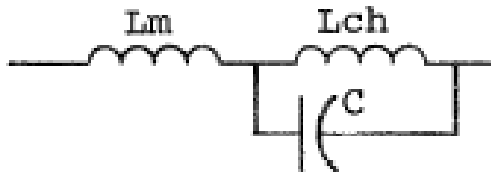


Power Supply Experiments at E4R

- ◆ Motivation: To make the existing RF system capable to accelerate more particles
- ◆ Experiment 1: Reduce the repetition rate from 15 Hz to 12 Hz
 - Test successful
 - But rejected by the Control Dept because of its large impact on the clock system
- ◆ Experiment 2: Dual harmonic resonant (15 Hz + 12.5% 30 Hz)
 - Purpose: To reduce the peak RF power by 25%
 - Design and fabrication of the 2nd harmonic choke is under way

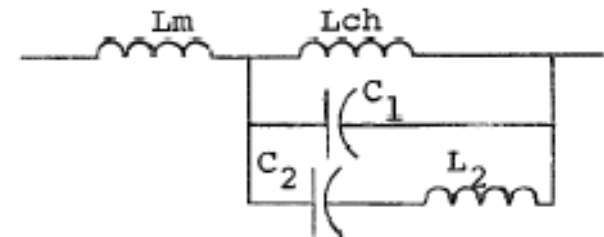
Booster Cell with 2nd Harmonic

Single harmonic



L_m	20.4 mH
L_{ch}	40 mH
C	8341 μF
f_0	15 Hz

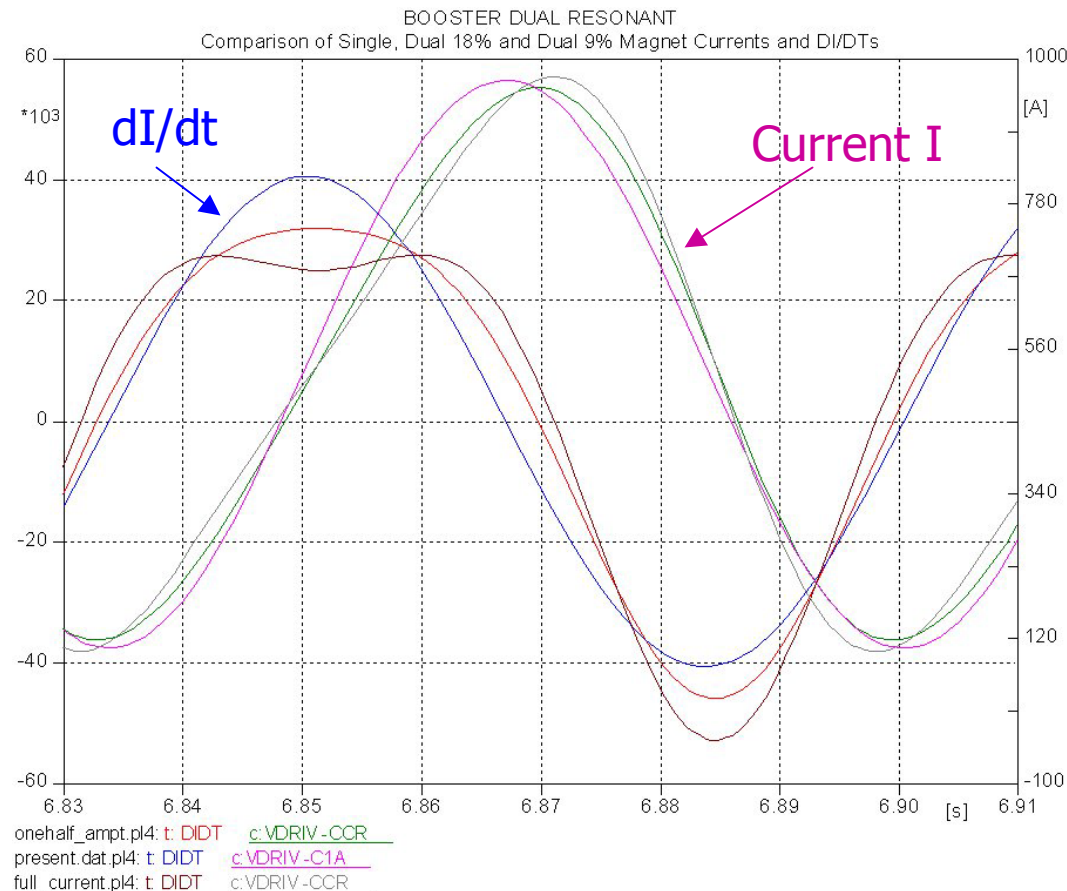
Dual harmonic



L_m	20.4 mH
L_{ch}	40 mH
C_1	6110 μF
L_2	26 mH
C_2	1480 μF
f_1	15 Hz
f_2	30 Hz

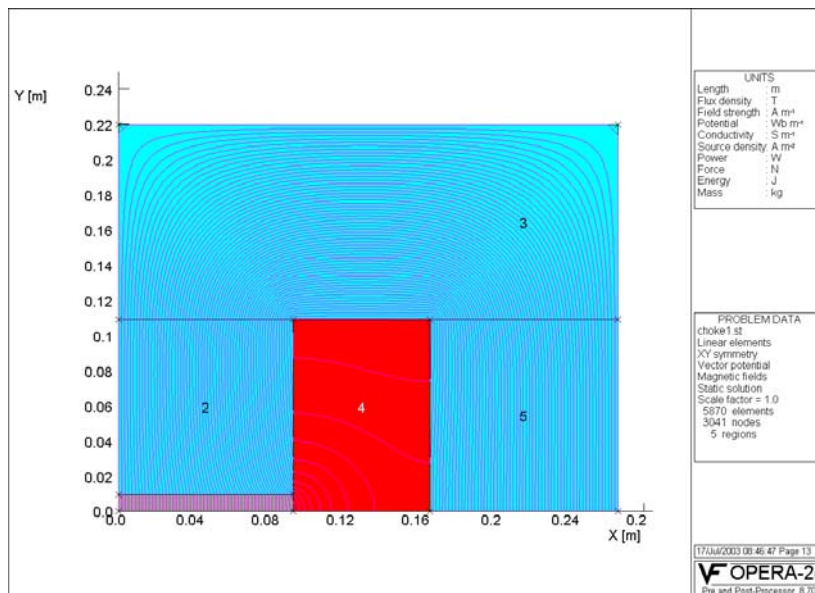
Dual Harmonic Current and dI/dt

(3 cases: dual 0%, 9%, 18%; courtesy D. Wolff)

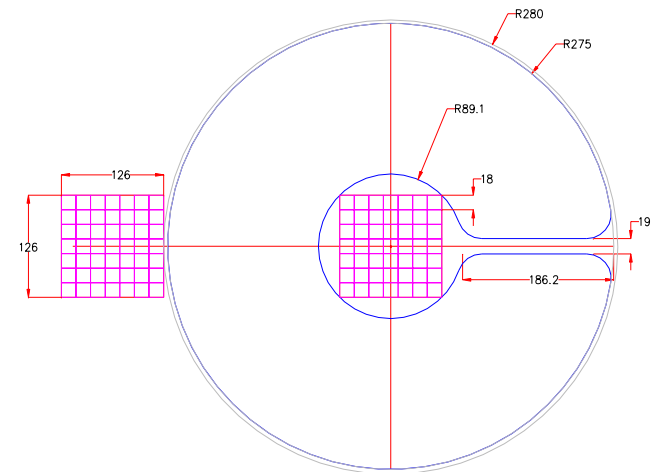


Two 2nd Harmonic Choke Designs (Courtesy V. Kashikhin)

H-magnet type



Toroidal transformer type



Summary

- ◆ Thanks to many people's commitment and a good collaboration among several departments, divisions and universities, the Booster study is making steady progress.
- ◆ This study is making the Booster a better machine.

Questions?
